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An integrated assessment approach for estimating the economic impacts of climate change on River systems: An application to hydropower and fisheries in a Himalayan River, Trishuli

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ABSTRACT

Changes in snow and glacier melt and precipitation patterns are expected to alter the water flow of rivers at various spatial and temporal scales. Hydropower generation and fisheries are likely to be impacted annually and over the century by seasonal, as well as long-term changes, in hydrological conditions. In order to quantify the effect of climate changes on hydropower and fisheries, we developed an integrated assessment framework that links biophysical models (positive degree-day model, hydrologic model, run-of-river power system model, and fishery suitability index) and economic models. This framework was used to demonstrate the framework's utility for gaining insights into the impacts of changed river flow on hydropower and fisheries of the Trishuli River in the High Mountain Asia (HMA) Region (from the Hindu Kush and Tien Shan mountain ranges in the west to the Eastern Himalaya). Remotely sensed and in situ data were used to quantify changes in snow and glacier melt in Langtang glacier and resultant change in hydrologic flow in the Trishuli River upstream of the Trishuli hydropower plant. Future discharges were projected using climate data derived from the Cubic Conformal Atmospheric model with 50-km resolution in Representative Concentration Pathway (RCP) 8.5 and RCP 4.5 climate scenarios. Results suggest that, in the future, the Trishuli River will experience modest increases in the economic value of the hydropower resource and fisheries as a result of higher snow and glacial melt. Increased flow in the months of March and April attributed to increased glacier melt translated to an increase in electricity generation. However increased flow in June and July when the snow and glacial melt peak is coupled with monsoon precipitation could not be fully utilized due to hydropower plant capacity constraints. Fishery suitability in the Trishuli River would be greater than 70% of optimal under both RCP 4.5 and RCP 8.5. Power economic results do not vary significantly for the next thirty years because flow increases under RCP 8.5 and resultant energy production are more pronounced in the later part of the century. The framework utilized in this study can be expanded in the future to analyze hydropower infrastructure as well as fisheries conservation in the upstream HMA basins from Afghanistan through Bhutan.

1. Background and introduction

Climate-mediated changes in the melting of snow and glaciers and in precipitation patterns are expected to alter the flow of the rivers at various spatial and temporal scales (Field et al., 2014; Immerzeel et al., 2009; Akhtar et al., 2008; Hock et al., 2005), which in turn could impact socioeconomics of the regions (Barnett et al., 2006; Viviroli et al., 2007, Moors et al., 2011). Himalayan Rivers provide the basis for food and energy production for more than a billion people and support diverse ecosystems in downstream areas of the High Mountain Asia (HMA) region that stretches from the Hindu Kush and Tien Shan mountain ranges in the west to the Eastern Himalaya. Because the economic value of a river depends on economic activities governed by river flow, changes in seasonal and long-term hydrological conditions due to climate change may have far-reaching economic consequences annually and over the century.

While energy production is the priority in the HMA region, agriculture is the backbone of the economy and nature-based tourism is a

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major source of the Gross Domestic Product (GDP). Countries of the region have plans to develop hydropower resources to meet rising electricity demands for the growing and developing population. Rivers are also the basis for irrigated agriculture and the livelihood of rural populations. The Ganga-Yamuna and Brahmaputra Rivers are used to irrigate 0.5 million km^2 (60% of irrigated land) and 6000 km^2, respectively, in India (GOI, 2010). Fish biodiversity supported by the rivers is the main source of income for 0.5 million fishermen in India and 30,000 in Nepal (FAO, 2012).

Critical climate change impacts have been demonstrated in the HMA region. According to an Intergovernmental Panel on Climate Change (IPCC) report (Field et al., 2014), an increase of 2.4 °C was observed in the mid-latitude semiarid region of Asia during the cold season (November to March) from 1901 through 2009. From 1967 to 2012, snow cover in the northern hemisphere decreased by an average of 1.6% (0.8% to 2.4%) per decade in March and April and by an average of 11.7% (8.8% to 14.6%) per decade in June (Field et al., 2014). Climate modeling conducted using Representative Concentration Pathway (RCP) 2.6 predicts that temperatures in the mid- and late-21st century would increase by 2 °C to 3 °C above the late-20th-century baseline over the high latitudes in South Asia (Field et al., 2014). Such increases in temperature would result in an accelerated thaw of glacial ice packs. The report projected that spring snow cover in the hemisphere will decrease by 25% under RCP 8.5 by the end of the 21st century.

The contribution of snow and glaciers to river flow for high-altitude areas is important for hydropower production in Nepal. Recent studies by Racoviteanu et al. (2013); Brown et al. (2014), and Gupta et al. (2015) show that glaciers contribute more than 50% of the total annual streamflow in the Langtang River Basin. However, the glaciated area in Nepal decreased by 24% from 1977 to 2010 (Bajracharya et al., 2014). Given the heterogeneity in topography and distribution of glaciated areas within river basins, pressing questions include (1) to what extent does projected climate change affect snow and glacier melt; (2) to what extent does melting dynamics change the runoff regimes in these rivers; and (3) what economic sectors are significantly affected by climate change? While the contribution of snow and glaciers to river runoff has been studied in a few selected HMA river basins (e.g., Brown et al., 2014; Alford and Armstrong, 2010; Bookhagen and Burbank, 2010), the spatiotemporal impacts of climate-mediated changes on streamflow are not well understood for the rivers in the region. Furthermore, it is important to understand the magnitude and extent of such changes on economic values for specific downstream resources and the effects on regional economics. The estimated economic value of such impacts on river flow is crucial information required by the Nepal government for effective water resource planning and management.

While changes in flow would have a range of potential impacts on downstream ecosystem services, our focus is on the effects of changes in the timing and magnitude of flows on the economics of hydropower generation and downstream fisheries. Currently Nepal generates 92% of its electricity from hydropower (Asian Development Bank, 2012) and the peak annual electricity demand is almost 1000 MW. To meet the expected rapid increase in future demand and trade with India, the Department of Electricity Development granted licenses for development of new hydropower plants that if constructed would provide 5465 MW of additional generating capacity (NEA, 2015).

The ability of decision makers to understand the economic risks of climate change on existing and planned hydropower is hampered by the uncertainty of climate-based changes in river flow and the lack of understanding of the linkages between river flow regimes and the economic benefits generated by river systems through energy production and ecosystem services. This places investments in infrastructure development for hydropower, fisheries, and irrigation at high risk. A greater understanding of the impacts of climate change on river flow, especially how that translates to economic return from existing and proposed hydropower plants and how downstream river functionality would be affected under altered water availability scenarios, is critical to the sustainable management of river basins within the region.

This paper was developed as part of a larger study funded by the National Aeronautics and Space Agency (NASA) for understanding these potential effects in the HMA region. Here we describe an integrated assessment framework for evaluating the impacts of climate-mediated changes in river flow on downstream ecosystem services and demonstrate the application of the framework to a portion of the Trishuli River basin in Nepal. While the framework was developed for analysis of hydropower plants, agriculture, and fisheries, the example presented in this paper focuses only on a hydropower plant in Trishuli River and fisheries upstream and downstream of the plant.

2. Methods

2.1. Framework for assessments

An overarching question the HMA region is facing is how climate change will impact the economies of these developing nations, which are based on climate-sensitive energy production, agriculture, and nature/biodiversity-based tourism. The total economic returns from hydropower production, food (irrigated land) production, and fisheries are expected to change in the future as a result of climate-mediated changes in river runoff. The water-energy-food nexus will be a fundamental and increasing challenge (Russi et al., 2013) as the unique ecosystem is expected to be greatly impacted in the region. Water resource managers in the region will need to address trade-offs regarding the development of additional hydropower plants to meet energy needs and maintain downstream ecosystem services in order to maximize net long-term gains.

Our assessment framework integrates an economic valuation model with biophysical models of climate, remote sensing, snow and glacier hydrology, energy production, and environmental performance (Fig. 1). The framework is based on the integrated assessment approach (Forney et al., 2013; Antle et al., 2001) to estimate changes in total economic values corresponding to changes in physical conditions. Economic value is estimated as the value of ecosystem services from the river. Ecosystem services are attributed to provisioning, regulating, cultural, and support services such as hydropower generation, irrigation, drinking water, flood control, water supply to wildlife, rafting, fishing, and waste assimilation services. While the framework can be applied to estimation of all ecosystem services, our focus is only on the values of hydroelectricity and fisheries. Controlling future floods may become increasingly important under a warmer climate scenario. In our study we focused on current run-of-river hydropower plants that cannot be used

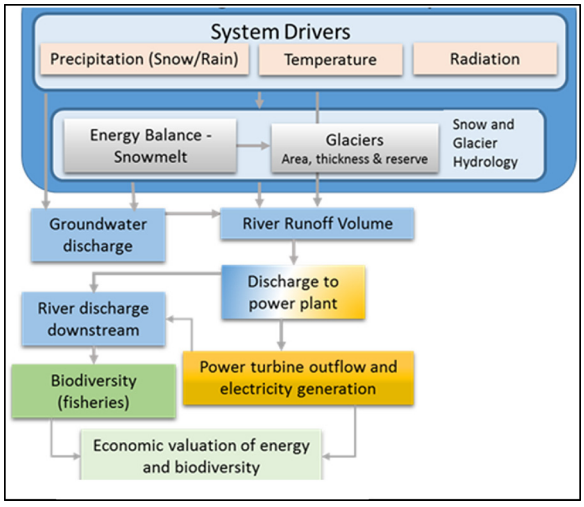

Fig. 1. Integrated assessment framework schematics.

for flood control. Data availability for drinking water systems, informal irrigation systems as well as the other regulating and cultural ecosystem services limits further analysis of these sectors. Furthermore, it is premature to conduct flood control analyzes at this point in time because of large uncertainties associated with the future development of reservoirs. This could be analyzed in future studies when more information is known about its future development.

Economic impacts are estimated based on changes in electricity output and fisheries production resulting from increases in flow due to climate drivers. Climate models for dynamic downscaling are used to generate historical reconstructions and projections of high-resolution precipitation (rain and snow) and temperature data. The climate model results feed into a remote-sensing component that uses multiple datasets pertaining to system environmental drivers and surface processes (e.g., snowpack and freeze/thaw state) in order to generate melt-runoff estimates. Snow and glacier hydrology models provide the estimates of river flow needed to evaluate effects on electricity generation and fishery suitability. Estimates of electrical generation and fisheries suitability are used to evaluate the potential impacts of climate change. The change in economic value is estimated as the net difference between the expected future economic value of the ecosystem services under baseline conditions and for a specific climate scenario.

2.2. Example: application of framework to the Trishuli River Basin

2.2.1. Study area

We applied our framework to the Trishuli River Basin, a subbasin of the Gandaki River Basin of the Ganga River Basin (Fig. 2). The Trishuli River originates at Kirong Tsangpo in the Tibet Autonomous Region of China. The Trishuli River flows into the Narayani River, which runs through Chitwan National Park in Nepal and into the Gandaki River in India.

Currently, five operational hydropower plants with a total capacity of 70.1 MW are located in the Trishuli River basin. Three of the five operational plants (the Chilime, Trishuli, and Devighat plants) are located from north to south on the mainstem of Trishuli River, with a capacity of 22.1 MW, 24 MW, and 14.1 MW, respectively. The Chilime

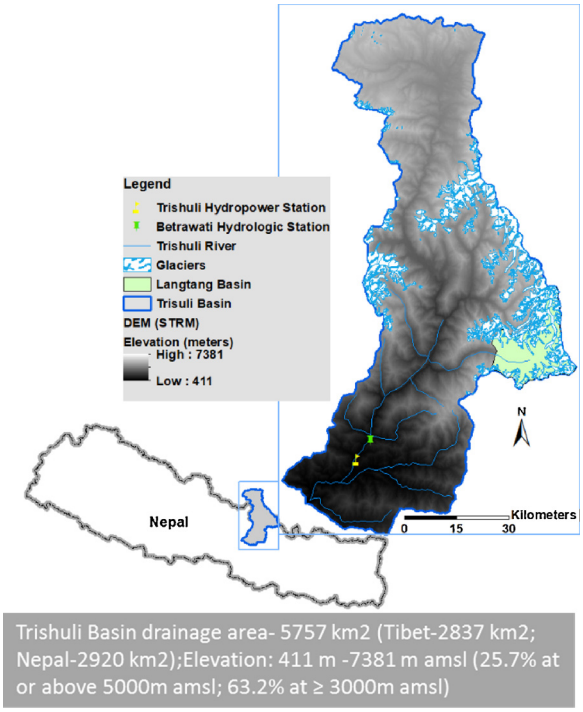

Fig. 2. Hydropower plants (operational and under construction), hydrology and meteorology stations in the Trishuli basin.

plant started operation in 2003/2004 with an annual average generation of 146 GW h. The annual generation potential of the Trishuli and Devighat power plants is 163 GW h and 144 GW h, respectively. Actual annual generation at these plants in FY 2014–2015 was 77% (125 GW h) and 68% (98 GW h) of annual potential, respectively (NEA, 2015).

Four stream gauging stations are located in the Nepal side of the basin—Langtang, Palankhu Khola, Betrawati, and Tadi. The Langtang station is located upstream of the Betrawati station at an altitude of 3670 m amsl. The Langtang station measures flow of the Langtang River, which drains from Langtang subbasin of 353 km^2 (Elevation 3652–7215 m amsl). The Betrawati station is located on the Trishuli River mainstem upstream of the Trishuli hydropower plant (Fig. 2) at an elevation of 600 amsl and receives a flow from a drainage area covering 81% of Trishuli River Basin. The flow records at this location have been well maintained since 1977. In addition, five meteorological stations located at Timure, Thamachit, Nuwakot, Kakani, and Dhadingbesi are in the basin at altitudes ranging from 1003 amsl to 2064 amsl. The stations have been recording conditions from over a period of 16 to 33 years.

An example of an economic valuation of the hydropower and fisheries sectors is presented using an integrated assessment framework in order to gain insights into the economics of the two sectors in Trishuli River Basin. In addition to hydropower and fisheries, a number of other ecosystem services are provided by most of the rivers including irrigation for agricultural production (commercial and sustenance), flood protection, tourism, and drinking water. The Trishuli River flows through gorges until it mixes with other tributaries of Gandaki River in the plains. There are no irrigation or drinking water systems with systematic data on water use in the Trishuli River basin; therefore economic value of irrigation and drinking water are not included in this analysis. Additionally water supply is abundant relative to its current and projected demands in Trishuli Basin. It is therefore anticipated that the impact of climate change on the economic value of water for these purposes would be inconsequential. The only other potentially measurable economic benefit of the river is water-based tourism; namely, white water rafting. The Trishuli hydropower plant is a run of the river type hydropower plant located at 50 km river miles upstream of the rafts put-in point. As a run of the river hydropower plant, the water required for rafting is not affected by the water release pattern of the Trishuli hydropower plant.

2.3. Climate drivers

Climate data were derived from the Cubic Conformal Atmospheric model with 50-km resolution in Representative Concentration Pathway (RCP) 8.5 and RCP 4.5 climate scenarios out of the four greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively) that depend on how much greenhouse gases are emitted in the years to come. The future climate projections under the lower medium stabilizing emission scenario RCP 4.5 and high emission scenario RCP 8.5 were used to estimate daily river channel flow. The projections driven by these two scenarios provide a range of climate responses, especially a range of temperature increase from the low medium to the high levels without considering mitigation scenario (RCP 2.6). The two climate scenarios selected therefore represent plausible “bookend” futures. Most other climate change scenarios, and hence associated economic impacts would fall within the range of the two scenarios analyzed.

2.4. Hydrologic modeling and projections

Hydrology of the basin was evaluated by considering significant

effects of climate-mediated changes in snow and glacier melt on hydrologic dynamics. The Langtang River subbasin was selected as a representative high-altitude hydrologic system (39% of basin area is covered by glaciers) for detailed hydrologic modeling and the resultant hydrologic responses from the Langtang River subbasin were used for flow projections at the Betrawati gauging station in the area upstream of the Trishuli hydropower plant for the two bookend future climate scenarios.

The high-altitude, glaciated hydrologic system is typically driven by temperature effects on water stored in various forms with precipitation dynamics. The runoff from the Langtang River subbasin was estimated using the modified Positive Degree Day (PDD) model. This model is based on the assumption that the melting of snow and/or ice during any particular period is proportional to the positive degree-day linked by the positive degree-day factor (Braithwaite and Olesen, 1989). This approach is appropriate in regions with scarce data (Kayastha et al., 2000a; Hock, 2003).

The Langtang River subbasin was divided into 36 elevation zones with a zone width of 100 m. Temperature and precipitation at each elevation zone of the subbasin were obtained by using the temperature lapse rate of 0.59 °C $(100\ m)^{-1}$ (Pradhananga et al., 2014); precipitation gradients (Kayastha and Shrestha, 2017) were applied to the temperature and precipitation data from the Langtang meteorological station at Kyangjing. The relation between monthly air temperature and snowfall percentage obtained on Glacier AX010 (Kayastha et al., 2005) was used to separate snow and rain from the total precipitation. In each zone, the daily snow and ice melt from the glacierized and glacier free areas was calculated using the following relations:

$$M = \begin{cases} k_{s\,or\,b} \times T \text{ if } T>0 \\ 0 \text{ if } T \le 0 \end{cases} \quad (1)$$

$$M = \left(\frac{k_d}{k_b}\right) \times k_b \times T \quad (2)$$

where M is the snow or ice melt (mm d^{-1}), T is the air temperature (°C), and k is the positive degree-day factor for snow (k_s) or ice (k_b) or ice melt under debris layer (k_d) (mm d^{-1} °C^{-1}) as found by Kayastha et al. (2000a, 2000b, 2003) for Glacier AX010 and Yala Glacier in Langtang Valley. Because debris is thicker in the lower part of the glacier, a $\left(\frac{k_d}{k_b}\right)$ value of 0.50 was used for the mean elevation zones up to 4350 m amsl, and 0.58 for higher elevation zones (Kayastha et al., 2005).

The snow and ice melt, precipitation contributing to runoff, and the base flow from each elevation zone were calculated using Eq. (3) and integrated using Eq. (4) to derive the entire basin's flow (Q).

$$Q_z = (Q_r \times C_r) + (Q_s \times C_s) + Q_b \quad (3)$$

$$Q = \sum_{z=1}^{z=36} Q_z \quad (4)$$

where, Q_z, Q_r and Q_s are the flow from zone Z, direct precipitation, and snow and ice melt, respectively; C the runoff coefficient (Q_b the base flow, derived using Subramanya (2010).

The flow Q is then routed to the basin outlet as per the recession equation (Eq. (5)) given by Martinec (1975).

$$Q_n = Q*(1\text{-}k) + Q_{n\text{-}1}*k \quad (5)$$

where Q_n is the river flow at the basin outlet on the *nth* day, and k is the recession coefficient given by Martinec and Rango (1986). The constants x and y computed from equation 11 are 0.99 and 0.012, respectively, for the Langtang River.

The Betrawati area, where the Trishuli hydropower plant is located, is in the lower part of the Trishuli hydrologic system. It has similar characteristics to the Langtang subbasin that is driven by both snow and ice melt and precipitation dynamics. The average monthly flow measured at the Betrawati gauging station ranged from 34.64 m^3s^{-1} (in March) to 904 m^3s^{-1} (in July) over the period 1977–2013. The peak flow in the summer is consistent with peak glacier melt as characterized in the Langtang subbasin. Even though the majority of glaciers in the Trishuli River Basin is in Tibet, China, there were no observations available for this study. Therefore, a regression model was developed based on flow data at the Langtang and Betrawati stations (2008–2013). The methodology considered seasonal changes in the correlation between the two flows using dummy variables for each month justified with p-value.

The projected change in discharge at the Betrawati station over the period of 2020–2099 was used to estimate the impacts on electricity generation at the Trishuli power plant and fisheries upstream and downstream of the power plant.

2.5. Estimation of economic value under various flow scenarios

The objective of the economic analysis is to provide preliminary insights for water resource managers specifically those responsible for granting licenses for hydropower development in Nepal under limited information available on hydrology and changing climate. The rights for consumptive and non-consumptive use of water are not well established. The Nepal Government uses up-to-date information prior to providing licenses to hydropower development; however the information available is limited. In this backdrop, rather than individual hydropower plant's profits, understanding of the long term impact of climate change on power plants and fisheries would be useful. To that end we present a study of one operating power plant in this paper. The economic value of a river system, V_r, was estimated as the summation of the values of the economic activities associated with the ecosystem services provided by the river.

$$V_r = \sum_{n=1}^{s} V_s \quad (6)$$

where V_s is the value of an ecosystem service "*s.*" River water is used to achieve multiple objectives in a river segment, and the quality, timing, and quantity of water released from upstream sources can affect downstream economic activities. A host of ecosystem services such as provisioning services (e.g., hydroelectricity, irrigation), cultural services (e.g., rafting, fishing) could be incorporated in the framework. As previously stated, the Trishuli River does not serve formal irrigation and drinking water systems; therefore, the economic value for these two water uses considered in this study. Furthermore, the Trishuli hydropower plant is a run of the river hydropower facility located 50 km upstream of where boaters launch their rafts, the water release pattern of which does not affect rafting activities. Therefore, the only consequential economic impacts as a result of climate change is tourism and fisheries.

The framework for an assessment of two interdependent ecosystem services, hydropower and fisheries. V_r is estimated as the sum of the values of the hydropower (V_H) and the fisheries (V_F). As the estimated value includes the value of a subset of ecosystem services, the estimate is a lower bound estimate.

Water-allocation decisions of a social planner ideally should maximize the total economic value generated from a river based on the energy and environmental goals of the area, biophysical characteristics and endowments of the basin, and resultant production potential over a period of time.

The decision maker's objective function will thus be:

$$Max\, f(x) = Max\left[\left(\sum_{s=1}^{n} [V_h + V_f]\right) * \left\{\frac{r*(1+r)^t}{(1+r)^t - 1}\right\}\right] \quad (7)$$

Subject To. $x_1 - (Q_1 - Q_s) \le 0$

$x_2 - x_1 \le 0$

$\alpha_1 - x_2 \leq 0$

where Q_1 is the flow of water in m^3s^{-1} in the river upstream of hydropower plant, x_1 is the amount of water released from hydropower plant, x_2 is the flow received by fisheries, α_1 is the minimum water required by fisheries, r is the discount rate, and t is the number of years. For the run of the river power plant such as the Trishuli plant, Q_s is zero.

As a run of the river power plant without any dam for water storage, the inflow Q_1 is equal to the discharge from Trishuli hydropower plant, x_1 plus water that has been diverted about the plant's turbines. The Trishuli power plant operates as a run-of-the-river generation facility and there is currently no ability to store water and/or manage hydropower production and river flows. The water supply in the river is adequate and is expected to increase towards the later part of the century. Therefore, optimization based on managing the timing and magnitude of flows through the power plant to shape energy production and allocate water for fisheries in order to maximize its economic values is impossible. More importantly the objective of the economic analysis is to provide preliminary insights for the water resource managers specifically those responsible for granting hydropower development licenses in Nepal, who are operating under limited hydrologic and climate change information. In this backdrop, rather than individual hydropower plant's profits, we focused on connecting the cryosphere to the power economics for understanding of the long term impact of climate led change on hydrology on power plants and fisheries.

Electricity generation from hydropower depends only upon the inflow of river water and the attributes of the hydropower facility. For computational efficiency we decided to use a fast simulation model under a large number of unit on/off states based on historical outage levels in order to estimate power production under a range of possible operational conditions. In the context of a number of hydropower facilities in pipeline and some with dams, Eq. (8) could be useful. For this case study, the economic value is estimated as the sum of the economic value of hydropower and fisheries.

The value of hydropower (V_h) is the sum of the direct value of electricity produced to hydropower company and the indirect value of the electricity to the users (Eq. (8)).

$$V_h = (Q_E \times P_E) + SB_E \quad (8)$$

where Q_E is the electricity generated under the constraints of downstream environmental flow and P_E is the price per kWh. The indirect benefits of the hydropower plants include the societal benefits from the use of electricity. The societal benefits of electrification (SB_E) include benefits from lighting facilities, household appliances, health benefits (due to improved health facilities, improved indoor air quality, and communications), educational benefits (e.g., increased study time at home due to improved lighting, improved quality of school equipment), global benefits from reduced greenhouse gas emissions, and increased rural enterprises. Rural electrification attributed to the hydropower plant is used primarily by households for lighting and watching television. According to a World Bank study (The World Bank, 2008) that estimated the benefits from rural electrification in developing countries from Asia, the total benefit ranges from US$ 0.20 to US$ 0.60 per kWh (excluding home business benefits). The societal benefit per unit of electricity is estimated using a benefit transfer method and the World Bank's estimation of the benefits of rural electrification for South Asia.

To illustrate the potential impacts of changes in climate on the power grid, we developed a run-of-river hydropower simulation model that computes daily generation levels produced by each power plant unit. Daily power generations were projected for various climate change scenarios based on unit-level capacities, unit outage rates (i.e., on/off status), unit water-to-power conversion factors of the power plants and projected average daily river channel flow rates. Historical observations were used to estimate power conversion factors and unit outage rates.

The value of fisheries V_f was estimated using the predicted biomass of harvested fish under the given water release and the price of fish.

The monthly suitability of flow conditions for meeting fishery needs was modelled by comparing mean monthly predicted flows at the hydrology gauging station with monthly fishery flow targets developed by Rijal and Alfredsen (2015). The suitability of monthly flows for fishery maintenance was assumed to be 100% (i.e., optimal) if the mean monthly predicted flow was 95%–150% of the environmental flow target value; suitability drops to 0% when predicted flows were 0 m^3/s, and falls to 10% at flows greater than 250% of the monthly flow target. The monthly suitability scores for each year were used to develop an annual overall fishery suitability index. The annual overall fishery suitability index was calculated as the mean of the within-year monthly fishery suitability scores.

The fish biomass harvest rate was estimated using historic data on monthly fishery harvests from the Trishuli River (Joshi and Nepal et al., 2004) and recent estimates of fish biomass for reaches located upstream and downstream of the Trishuli Hydropower Station (Nepal Agricultural Research Council, 2017). Using the biomass estimates of Nepal Agricultural Research Council (2017) as a baseline value, monthly fishery productivity was calculated as a proportion of the annual catch to reflect monthly fishery harvest patterns identified by Joshi and Nepal et al., 2004. The monthly productivity estimates for the upstream and downstream reaches were then adjusted based on the calculated monthly fishery suitability scores to produce monthly predicted productivity estimates. It was assumed that the monthly fishery harvest would represent 1% of the monthly fish productivity estimates. Fishery harvests were projected for the 2020–2099 period under RCP 4.5 and RCP 8.5 using predicted flow conditions, corresponding suitability scores, and the estimated fish biomass production under the projected suitability score.

The impact of climate led change in river flow were estimated as the difference in value of hydroelectricity generated and fisheries under the projected flow conditions under climate change scenarios (RCP 4.5 and RCP 8.5) versus the business as usual scenario.

3. Results

3.1. Snow and glacier hydrology

The modified PDD model was calibrated for the period of May 2011 to December 2012 (Fig. 3, left panel) and validated for only the year 2013 because it is the only year with continuous daily hydrological data. The annual mean discharges of the Langtang River during calibration and validation periods were 9.1 $m^3\ s^{-1}$ and 8.5 $m^3\ s^{-1}$, respectively.

River flows were projected for Langtang River for the period 2020–2099 under RCP 4.5 and RCP 8.5 scenarios. The annual flow projected for the Langtang River subbasin under the RCP4.5 scenario exhibited an increase from 2020 to 2050 and a slight decrease from 2050 to 2099. Under the RCP8.5 scenario, discharge increased by 0.03 m^3s^{-1}; the maximum annual discharge of 11.1 m^3s^{-1} occurred in 2080 (Fig. 3, right panel). This trend was statistically significant. Most of the peak flows occurred in July as the peak glacier melt coincides with the monsoon peak.

3.2. Hydrologic projection

The regression model developed for the Trishuli Basin was used to project flow at the Betrawati station based on projected flows at Langtang for the period of 2020–2099 under two scenarios, RCP 4.5 and RCP 8.5. The model performed well with an R2 of 0.88 and a Nash-Sutcliffe efficiency of 0.87 (Fig. 4: left panel). Projected mean annual flow showed an increasing trend under the high emission scenario of RCP 8.5, and a slight decreasing trend under the low emission scenario

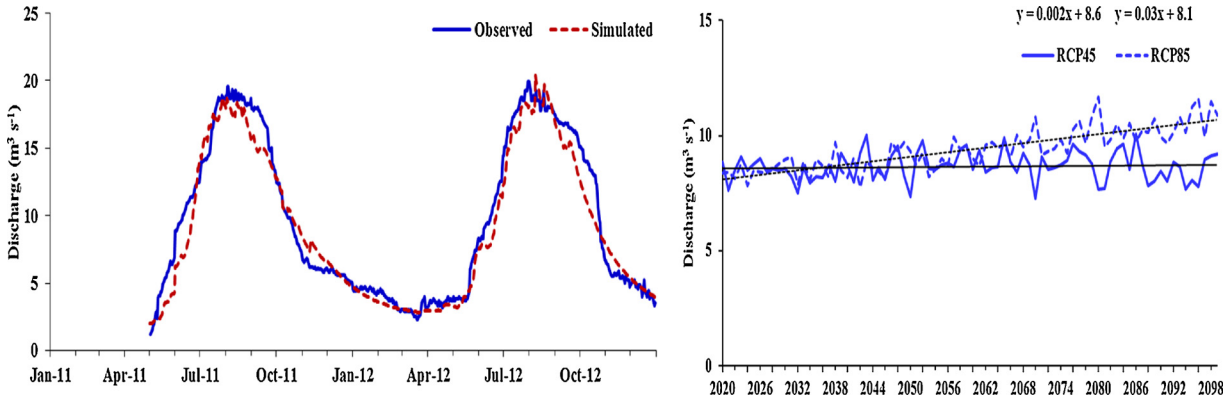

Fig. 3. Left: Comparison of observed and simulated discharges in calibration period (May 2011–Dec 2012) of the Langtang River; Right: Future discharge projection (420–2099) of the Langtang River.

of RCP 4.5 (Fig. 4: right panel). The difference in projected flow under the two scenarios is more pronounced in the later part of the century (Fig. 4: right panel). The simulated flow was slightly underestimated especially for flows > 600 m^3s^{-1}. The model has limitations because it does not specifically account for temporal and spatial heterogeneities over the large river basin due to a simple model using runoff coefficients. It was also based on limited information that relied on a low-flow period 2008–2013; therefore, it may not accurately describe higher hydrological conditions.

3.3. Hydropower generation

Daily and annual power plant generation levels at the Trishuli power plant were computed during the 2020–2099 study period under RCP 4.5 and RCP 8.5 climate scenarios based on discharge forecasts projected by the model discussed previously and historical operations data. Under the future scenario, it was assumed that historical unit characteristics would persist into the future. In addition, water diversion structures would continue to have current day operating capabilities that, at maximum, can only divert 85% of the main river channel water to the power plant.

Average monthly and annual generation between 2006 and 2010 were used as baseline. Annual generation levels and variability for the RCP 4.5 climate scenario were projected to remain similar to recent levels. Average annual generation for the baseline period was slightly over 128 GW h, which is very similar to the beginning trend line of RCP 4.5 of 129 GWH. Note that in Fig. 5 that the flow trend line under RCP 4.5 is nearly flat and that by 2099, annual generation is expected to increase by less than 1 GW h above 2020 levels under the RCP 4.5 climate projection. That is a change of approximately 0.8%. In contrast, due to higher projected river flow rates under RCP 8.5, annual generation levels are expected to be almost 4 GW h above the 2020 level. Most of this increase is expected to occur after the year 2050.

RCP 8.5 generation is expected to primarily increase in the winter and early spring. Generation levels are virtually identical for RCP 4.5 and RCP 8.5 between June and November. This occurs because diverted river flows into the power plant are projected to always be higher than the power plant maximum turbine flow rate. Higher water flow rates under RCP 8.5 therefore cannot be utilized for energy production during these months. In addition, the months of May and December have very little additional energy production. During the months of January, February, and March there is only a very small flow rate increase under RCP 8.5. Almost all of the additional water during these months is used to increase power generation. This is possible because flow rates under RCP 4.5 are typically below the maximum turbine level.

Only during events when several unit outages simultaneously occur are on-line turbines at the maximum flow rate during these winter months. There is a mix of increased turbine and non-turbine flows under RCP 8.5 in April, May, and December. When the flow rate under RCP 4.5 is significantly lower than average, the additional water flow can be routed through the plant's turbine to produce additional power.

The additional amount of energy projected under RCP 8.5 during the winter and early spring is expected to be minimal as compared to the baseline. It is expected however to be increasingly greater than baseline after 2065. The month of April will account for about half of the annual generation increase. The generation trend lines for April under RCP 4.5 and RCP 8.5 are similar between 2020 and 2040 and begin to rapidly diverge after 2050. By 2099, generation under RCP 8.5 is 1.5 GW h (18%) higher than RCP 4.5. However, the generation trend in August is nearly flat. The Trishuli power plant model results show that despite significantly higher flows under the RCP 8.5 climate forecast, only very modest increases in generation are expected. The plant is operated as a run-of-river facility because the reservoir is filling with glacial silt, the plant is undersized relative to the amount of water available, and generating units would need to be upgraded/refurbished to improve water use for power generation.

The above results are not necessarily indicative of what may

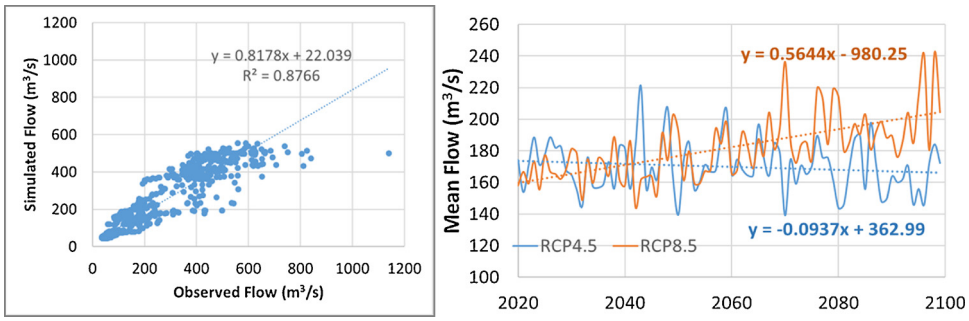

Fig. 4. Left: Observed and Simulated flow at the Betrawati Station of the Trishuli River; Right: Future flow projection at Betrawati.

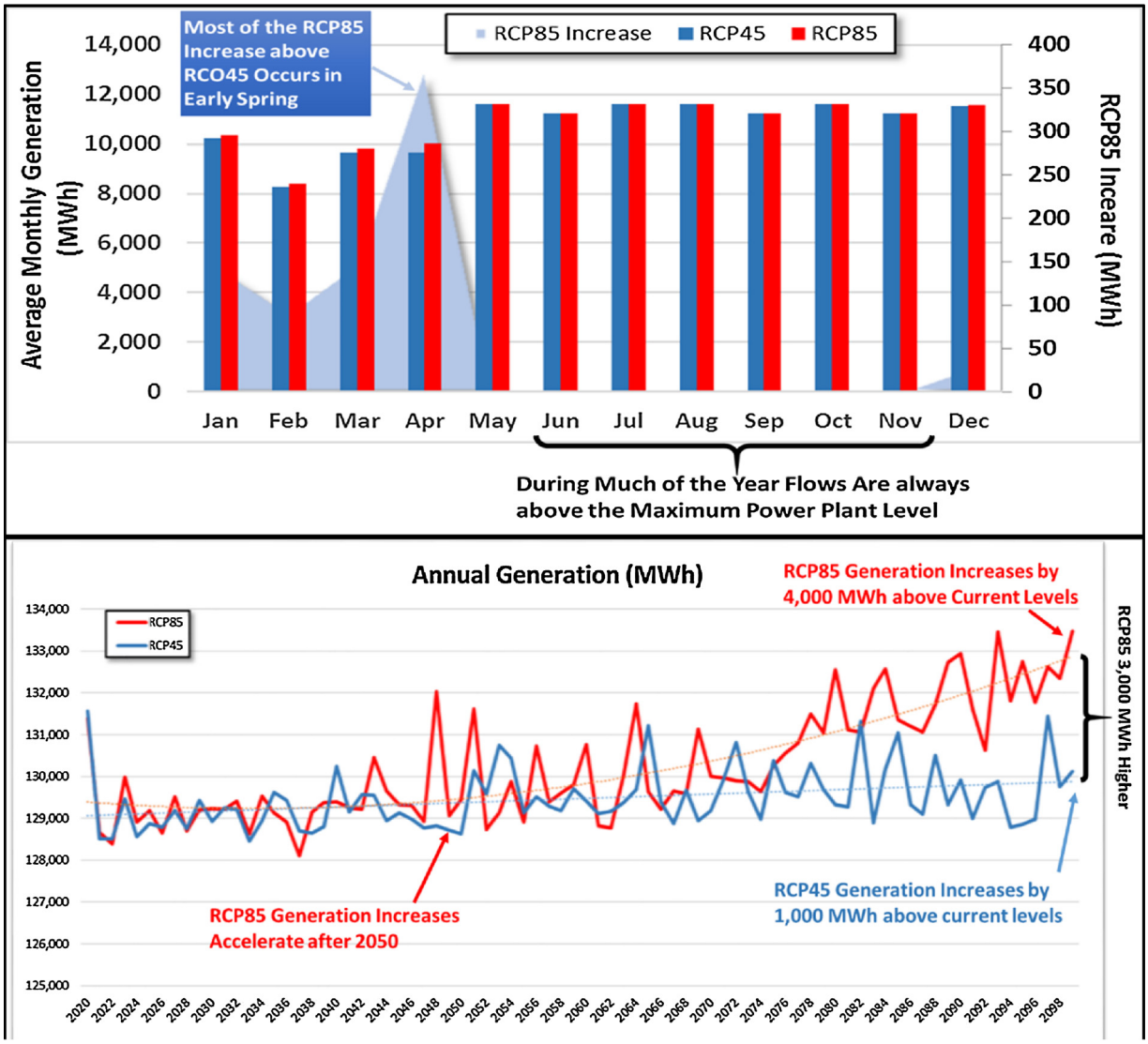

Fig. 5. Upper panel: average monthly generation levels. Lower panel: annual generation levels under RCP 4.5 and RCP 8.5 Climate Projections.

actually happen to the power sector as a whole because each hydropower plant is unique. Results will be highly dependent on the size, type, and efficiencies of hydropower plants that could utilize more of the forecasted increased flow under RCP 8.5. Detailed modeling of the entire hydropower system is needed to gain more insights into the impacts of higher river flows on the power sector.

Our analysis shows that more than half of the time hydropower generation is projected to be at its maximum potential under the relatively "cooler" climate change scenario RCP 4.5. This situation requires that large quantities of water are diverted passed powerplant turbines resulting in large electricity production losses. The amount of lost energy production potential is expected to increase under the warmer climate scenario (RCP 8.5). Employing a systemic impacts of changes on down-stream power/ecological resources and the power grid as a whole, decision makers should weigh the costs of upgrading hydropower plants for increased power production against economic and environmental gains.

3.4. Fishery production

Based on historic data for discharge at the Betrawati gauging station, monthly fishery suitability scores from January 1977 through November of 2014 ranged from approximately 39% to 100% (Fig. 6; lower left panel). The annual fishery suitability index for the 1977–2014 historic period ranged from approximately 67% to 100%; the annual spawning suitability index for the 1977–2014 historic period ranged from approximately 40% to 100%. Mean monthly fishery suitability scores for the entire historic period ranged from 89% to 100% and indicated that the months with the lowest mean suitability were May and June.

Fishery suitability modeling under the RCP 8.5 and RCP 4.5 climate scenarios (Fig. 6; right panels) indicated that April–June and August–September fishery suitability scores would decrease for the nearer-term projections (2031–2060) under both future scenarios as compared to the modelled baseline historic scores attributable to lower discharge levels in those months. In contrast, fish suitability for 2061–2090 period would be similar to baseline levels under RCP 8.5.

The baseline average fish biomass at Betrawati (20 ha) and Devighat (90 ha) are estimated to range from 66 kg/month (July) to 1923 kg/month (December), and 73 kg/month (July) to 2135 kg/month (December) over 1977 to 2013. The estimated baseline annual catch over the period ranged from 5150 kg to 5800 kg at Betrawati and 5718 kg to 6440 kg at Devighat. The projected annual fish biomass at Betrawati during the historic baseline period ranged from 280 kg/ha (RCP4.5) to 290 kg/ha (RCP8.5), while downstream of the Trishuli power plant at Devighat the projected fish biomass production for the

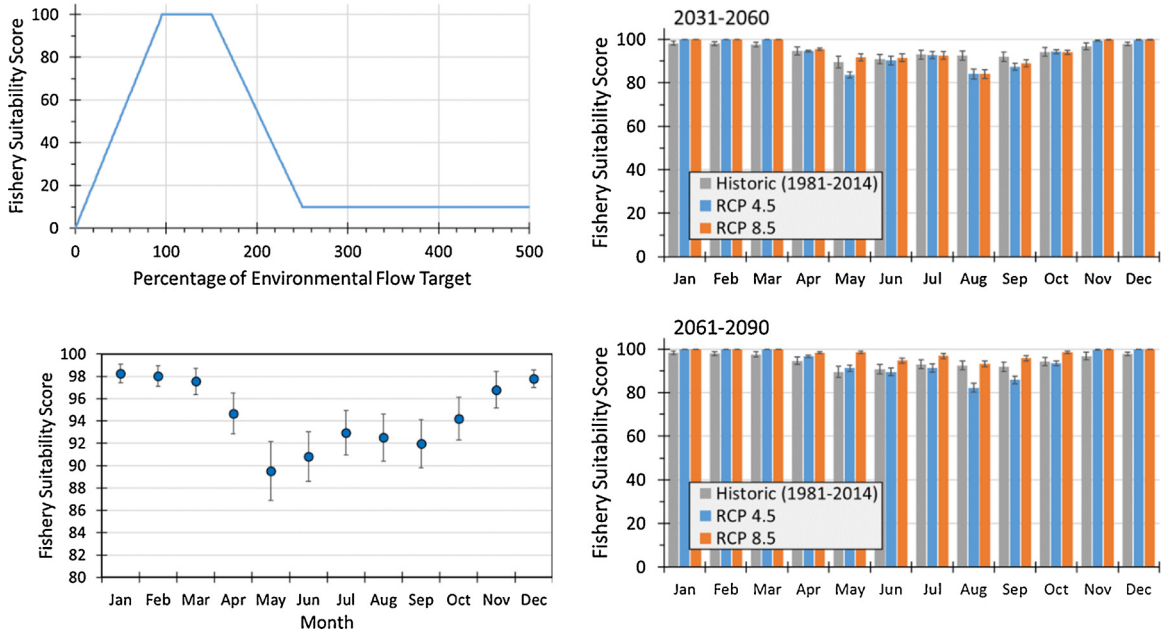

Fig. 6. Upper Left: Fishery suitability scores based on comparison of predicted monthly flows at the Betrawati Station to environmental flow targets developed for the Trishuli 1 hydropower project; Lower Left: Mean monthly fishery suitability scores. The panels on the right compare monthly historic (baseline) suitability scores to projected monthly suitability scores under RCP 4.5 and RCP 8.5 during middle and late portions of the 21st century.

baseline period ranged from 69 kg/ha (RCP4.5) to 71 kg/ha (RCP 8.5).

3.5. Economic valuation

The economic value of only the Trishuli hydropower plant and fisheries upstream and downstream of the plant was estimated for baseline and projected flow conditions. The economic value of the river segment was estimated first, as the sum of the revenue from electricity generated and fish production in the segment. Then the societal benefits of electricity generated were estimated. The estimation of societal benefits from the fisheries sector which requires collection of primary data from the fishing community community in the region is beyond the scope of this paper; thus the societal benefits were not included in the estimation. Thus, the economic value represents the lower bound of the estimates.

The estimated average annual revenue from electricity sales from the Trishuli power plant ranged from US$ 8.02 million (NRs 646 million) to US$ 18 million[1] (NRs 1.03 billion) from 1995 through 2015 based on data from the Nepal Department of Energy Development. The average annual revenue (1977–2013) from fisheries at Betrawati (upstream of the Trishuli power plant) and downstream of the Devighat area in the Trishuli River ranges from US$ 0.093 million (NRs 8.69 million) to US$ 0.99 million (NRs 12.24 million), with an average annual revenue of US$ 0.32 million to US$ 0.41 million. The total annual revenue from electricity and fisheries was estimated at US$ 8.12 million to US$ 19.16 million. All the values are estimated at 2016 constant dollar.

The projected annual revenue (2021–2050) for the Trishuli power plant under RCP 4.5 and RCP 8.5 ranges from US$ 10.9 million to US$ 11.00 million and $10.9 to $11.2 million respectively. As compared to baseline, the revenue under RCP4.5 ranges from a reduction of $0.08 million to an additional $0.06 million. Under RCP8.5 the change in annual revenue ranges from a reduction by $0.06 million to an increase of $0.22 million implying an increased uncertainty under RCP 8.5 as compared to that of RCP 4.5. The estimated monthly benefit is projected to increase by 3.5% and 4.1% for March under RCP4.5 and RCP 8.5 as compared to the baseline. For the months of May and June the estimated benefits do not vary under the two climate scenarios.

The projected average annual revenue from the fisheries sector for 2021 through 2050 is estimated to range from US$ 0.094 million (NRs 9.64 million) to US$ 0.12 million (NRs 12.09 million), respectively, under RCP 4.5 and RCP 8.5. As compared to the estimated total mean annual fisheries revenue for 1977–2014, the projected average annual revenue for 2021–2050 is higher by 0.1% to 6.1%. Power economic results do not vary significantly for the next thirty years because flow increases under RCP 8.5 and RCP 4.5 and resultant energy production is more pronounced in the later part of the century. As a result, the net present value of the revenue from the electricity sector for 2021 through 2050 were estimated at US $104.2 million and US$ 104.4 million under RCP 4.5 and RCP 8.5 respectively (constant dollars, year 2016). A discount rate of 7.5% was used following World Bank, which documents up to a 12% discount rate for developing countries. The NPV of fisheries sector ranged from US$ 2.46 million to US$ 3.08 million (2016 constant dollars) under RCP 4.5 and RCP 8.5, respectively.

The annual societal benefits from electricity generated from the Trishuli power plant for 2021 to 2050 ranges from US$ 25.6 million to US$ 26 million and US$25.7 million to US$26.4 million under RCP 4.5 and RCP 8.5 respectively. Because the changes in flow are expected to occur in the later part of the century, the net present value of the societal benefit of electricity generated from the Trishuli hydropower plant estimated for 2021 to 2050 under the two climate change scenarios RCP 4.5 and 8.5. The discounted net present value of the societal benefits from the Trishuli hydropower plant is estimated at US$ 349 million and US$ 350 million under RCP 4.5 and RCP 8.5 for the years 2021 through 2050.

4. Summary and discussion

This paper demonstrates the application of an integrated assessment framework that couples biophysical models for quantifying the impacts of climate change on glaciers and snow melt and its translation into downstream hydrology with economic models for monetizing the loss/gain attributed to climate-led changes in river flow. An example of

[1] The exchange rate increased from NRs 51.89 to 99.6 per U.S. dollar within 1995 through 2015

application of this framework in a North-South segment of the Trishuli Basin illustrated a systematic study of northern high elevation glaciers through southern plains and tied it to the economic value of the system. A suite of biophysical model results, including glacier and snow hydrology, hydropower, and fisheries models were fed into economic models in order to estimate the economic value of potential impacts of climate change on hydropower and fisheries.

Our models predicted climate change could lead to increase basin flows and subsequent impacts on hydropower and fisheries in a small segment of the Trishuli River. The flow is estimated to increase under RCP 8.5 scenario attributed to glacier retreat that would in turn lead to more water for hydropower and fisheries, and increased economic benefits. However, glacier mass is estimated to reduce to two-thirds of the present-day mass in the HMA region even when the target of 1.5°C is met and the estimated decline of glacier mass under RCP 4.5 and 8.5 are 49 ± 7% and 64 ± 5%, respectively (Kraaijenbrink et al., 2017). In addition, the flow may eventually be more dependent on precipitation (snow and rain) alone and the dry period are predicted to lengthen. A detailed investigation of the advancement of glaciers using long-term historic data may provide some insights into likely outcomes.

Seasonal variation in flow will become increasingly important when large power plants begin operations in the region. Water flow is expected to increase in early spring (March and April), attributable to snowmelt and glacier retreat/ice melt. An increase in annual electricity generation is expected to occur under RCP 8.5 in the winter and early spring. Fish suitability scores would decrease for April–June and August–September under both RCP 4.5 and RCP 8.5. Discharge is expected to decrease under both RCP 4.5 and RCP 8.5 for the month of May because it is the driest part of the year when the requirement for both electricity and fisheries is high (because of the spawning period). Increased monsoon flow may impact fisheries because the suitability index decreases to 10% when the flow is high during monsoon months. Impact of changed flow on fisheries has not been studied extensively in the region. A study by Das et al. (2013) estimated a decrease in fish spawning from 61% to 73% as compared to previous four years during 2009 attributed to a rainfall deficit of 28%.

The estimated economic benefits from the Trishuli hydropower plant is much higher than that of fishery upstream and downstream of the plant. However, the total economic benefits of fisheries is not included in this paper; only the estimated revenue is presented. Based on information gathered through recent communication with companies in Kathmandu, a 5-day fishing trip in four spots in the Trishuli River costs US$ 655. The annual income from fisheries is estimated at US$ 422/household from selling fish and consumption of food and protein (Sharma et al., 2015). Detailed investigation of the total economic value from the fisheries sector in the Trishuli River and changes in the value attributed to change in flow in various seasons of the month is required to fully understand the impacts on the sector.

In the backdrop of ongoing changes in water resource management policy of the government of Nepal and accelerated hydropower development, our study provides implications based on the integrated assessment framework and evaluation of total economic value of river systems in Nepal. The hydrologic forecast information provided could be useful for water resource management in the Trishuli river basin where thirty-three hydropower plants with a total capacity of 1042 MW are at various stages of development. Employing a systemic impacts of changes on down-stream power/ecological resources and the power grid as a whole, decision makers should weigh the costs of upgrading existing hydropower plants for increased power production against economic and environmental gains. The increased production and environmental gains are associated with higher flow during snow and glacier ice melt season. The glacier ice packs are shrinking and the melt volume will start reducing at one point. Because of the uncertainties associated with climate change coupled with limited information on glacier pack shrinkage, decision makers must also account for the financial and economic risks associated with future hydropower development plans. Such an analysis is useful but beyond the scope this current paper, however, it is highly recommended that this type of analysis be conducted in the future before major reservoir and hydropower investments are made in the snow and glacier melt dominated rivers in the HMA region.

This paper describes example results for the Trishuli River. It is the research team's first attempt at coupling multidisciplinary model components in this data scarce region. It was therefore necessary to use several assumptions and simplified modeling techniques that we plan to refine and improve upon throughout the ongoing NASA-funded research project. Higher resolution downscaled climate data (rather than the 50-km resolution was used for this study) and satellite imagery sentinel SAR to evaluate freeze and thaw in data scarce glaciated regions which are the critical inputs in projecting snow and glacier melt as well as downstream hydrology are expected to improve the estimations. The integrated assessment framework developed here could also be used for improving our understanding of impacts on all ecosystem services provided by the river beyond hydropower and/or fishery sector and distill information pertaining to water resources management decisions for the snow- and glacier-dominated river-basins in the Himalayas and elsewhere.

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